Comparison of Diagnostic Test Techniques on Laboratory Aged Water Treed MV-XLPE Cables

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Abstract

All major power utilities are extensively using XLPE insulated high voltage cables. One of the most important processes that can adversely affect the performance and reliability of these cables is water treeing phenomenon which occurs due to presence of moisture and electrical stress. In many utilities a large percentage of these cables are approaching the end of their designed life. The utilities are now faced to take decision to maintain, repair, refurbish, or replace such cables in their networks. Therefore, non-destructive diagnostic tests are required to assess the cable system through organized condition based asset management program. At the high voltage laboratory of King Saud University, 15 kV rated XLPE cables are being water treed through accelerated multifactor aging. Connected in parallel, three promising non-destructive testing techniques are keeping track of this deterioration. This methodology will not only compare these diagnostic methods but will also find the best approach that can be applied to test and classify 'in-service' aged cables.

Keywords: XLPE cable diagnostics, Accelerated cable aging, Water treeing, Dielectric spectroscopy, Return voltage measurements.

1. Introduction

For transmission and distribution of electrical energy, XLPE insulated high voltage cables are extensively being used and are playing a vital role in the electricity supply systems. These cables are subjected to several types of stresses when operated in the field. These stresses include exposure to chemicals, moisture, heat, mechanical forces and electrical stress. Consequently, the cable's dielectric properties degrade during service life. One of the most important degrading processes is water treeing phenomenon. Water treeing occurs due to presence of moisture and electrical stress. Elevated levels of ambient temperatures and presence of salts such as sodium chloride and copper sulfate can dramatically increase the water treeing in such cables.

The environmental conditions in Arabian Gulf region are characterized by high ambient temperatures, large contents of chlorides and sulfates in the soil and subsurface water and high water table. Furthermore, some of the cables have been in service for almost 30 years and may have approached the end of their estimated lives. As a result utilities are faced with critical decision to maintain, repair, rejuvenate or replace them. The decision should not be made on the age alone as cables do not age uniformly with time and thus any replacement program should be based on their condition rather than their age. Condition based maintenance can be successful only if the utility has access to reliable diagnostic tools to assess the health of cables.

In case of polymeric cables, a number of techniques to assess the condition of water treed cables have been introduced and most are based on the dielectric response of insulation to an applied electric field [1-5]. A review of different diagnostic technologies that have been successfully applied in the field to segregate the water tree deteriorated cables and classify them in good, to be repaired, or refurbished or to be replaced status was presented earlier [6].

A 15 kV, 50 mm^2 cross-sectional XLPE insulated cable loop of ~220 m length is currently undergoing multifactor aging as per AWTT protocol described in ref. [7]. So far this cable sample has undergone an aging period of 3000 hours. Three diagnostic techniques are being used to assess the impact of water tree degradation. These are: (i) RVM polarization spectroscopy, (ii) tan δ measurement at 0.1 Hz as a function of voltage, and (iii) tan δ measurement as a function of frequency and applied voltage in a frequency range of 0.1 to 0.001 Hz. The purpose of this investigation is to compare the performance of these techniques and to select the one that could serve the best in the field.

2. Cable Diagnostic Test Facility at King Saud University (KSU)

Of paramount importance for a cable testing laboratory that evaluates non-destructive diagnostic techniques is that it should have an arrangement of long term multi-factor aging of cables to impart water tree deterioration in the bulk of insulation that simulates the near in-service aging conditions. In this context AEIC-CS5-1994 specifies an accelerated water tree testing set up (AWTT) that utilizes water filled PVC tubes in which cable samples are immersed, while water is also injected in the interstices of the conductor. These authors, have reported earlier that instead of tap water if the cables surround aqueous solutions of 0.01 M $CuSO_4$, the initiation and propagation of water trees is augmented appreciably [8]. Therefore, a testing rig for AWTT was established at KSU, High Voltage Laboratory and $CuSO_4$ solution was used in the pipes connected to the reservoirs. Details of this set up are given elsewhere [9]. 15 kV rated MV-XLPE insulated single core cable of 50 mm^2 cross-section was prepared for AWTT set up. This set up was put in to operation and is shown in Fig. (1). Four cable sections each of 55 m length connected in a series loop are being aged at a time. Total loop's length is 220 m.

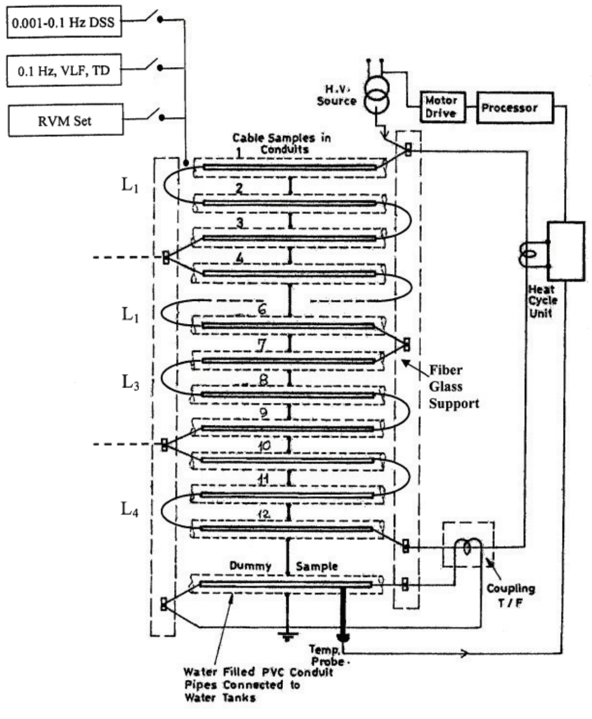


Fig. 1. Long term multifactor accelerated aging test set up for XLPE cables at KSU.

2.1 Cable Diagnostic Tools

Three types of off-line diagnostic techniques are being used as shown in the experimental set up. One of these is multi-frequency dielectroscopy set from HV diagnostics, model TD-90. It was originally designed to operate at 0.1 Hz and generate output sinusoidal voltage of up to 60 kV_{rms}. It was modified to operate in a frequency range of 0.001 to 1.0 Hz. It is equipped with operating software which gives complete picture of tan δ (TD) measurements together with real time display of the input/output data. The data transmission to the PC/lap top is via "Bluetooth" that eliminates the direct connection between the TD-90 and the data acquisition device. This instrument was used to measure TD values at (i) 0.1 Hz as a function of output voltage, and (ii) in a frequency sweep of 0.001 to 0.1 Hz as a function of voltage, thus giving two different types of diagnostic parameters. The third diagnostic tool used was RVM diagnostic system using Tettex RVM type 5462. This instrument was originally designed for transformer insulation diagnostic but it was adapted for XLPE cable diagnostics by using a 2.0 GΩ resister across its output terminals.

Measurements using all the three types of diagnostic techniques are in progress and data is being compiled on weekly basis. After aging period of 3000 hours, 5000 hours, 7000 hours and 10,000 hours the 55 m long sections from the tested cable loop will be removed one by one for water tree parameter analysis and determination of their retained dielectric strength (E_r). The three major data i.e. tree parameters, aging time, and E_r will provide the data bank for comparison of the performance of the three diagnostic techniques. The first 55 m long cable section was removed after completion of 3000 hours of aging. The results obtained are presented next.

3. Results and Discussion

After completion of aging period of 3000 hours the non-destructive and destructive test measurements were performed in the laboratory. Initially, non-destructive (diagnostic) tests were carried out while the cable loop was still in the water pipes. After completion of diagnostic measurements, part of this aged cable was removed and it was cut into 10 m long samples for AC breakdown test to determine their breakdown voltage (V_b) and remaining dielectric strength (E_r) where $E_r = (V_b/t)$. This cable had average insulation thickness of 4.5 mm. For water tree analysis, 10 cm long sample was taken out from each cable sample close to the breakdown channel. The results obtained from two types of tests were then analyzed and compared.

3.1 Non-Destructive Measurements

(a) Measurements Carried Out With RVM Set

Generally the return voltage of an insulation is a phenomenon of depolarization and conduction processes and thus a function of the dielectric response. The measurement of the return voltage comprises of three steps (see Fig. 2). Firstly a voltage step with a duration of 'T_c' is applied to the cable, which leads to a charging of the geometric capacitance and to a polarization of the dielectric. In the second step, the cable is short circuited for a short time (T_d) to remove the free charges from the electrodes of the cable capacitance. At that time the depolarization of the insulation starts resulting in a displacement current within the dielectric. In the third step, after the free charges have vanished, the short circuit switch is opened. As the depolarization of the dielectric continues. The change of the return voltage (RV) with time is a result of the gradual decrease of the polarization i.e. the relaxation of the excited dipoles. Without other additional influences a continuous increase of the return voltage occurs after reaching a peak value the return voltage decreases.

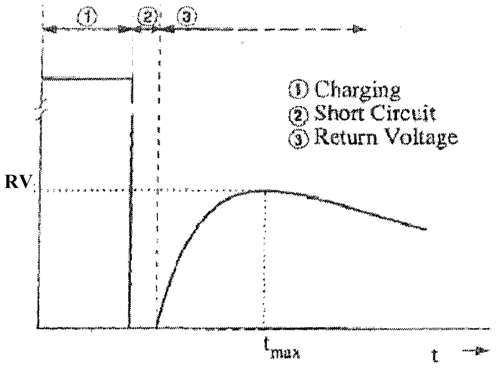


Fig. 2. Principle of return voltage measurement.

Fig. (3) compares '$RV-T_c$' polarization spectrum of a new (wet) XLPE cable and a 2000 hour heat cycle aged cable sample. Here T_c is the charging time. It is clear that new cable exhibits two distinct peaks at 0.5 s and 50 s, respectively. This effect is similar to reported by others [9]. However, in case of aged cable sample the RV amplitude has decreased while peaks have become distorted. Although it is well established that with heat cycling the number density of water trees increases manifold, therefore the dielectric response should exhibit peak with higher RV amplitude. To overcome this problem Januz et al. [10] proposed a model for water treed cable in which the technique of division spectra was used which should indicate a distinct peak at $T_c \leq 0.1$s on a plot of (B/A) as a function of T_c without requiring a reference '$RV-T_c$' spectra of new cable. Here B = (T_d/T_c = 10) and A = (T_d/T_c = 2), where T_d = depolarization time. Based on this hypothesis several division spectra were plotted using the present data but they produced inconsistent results.

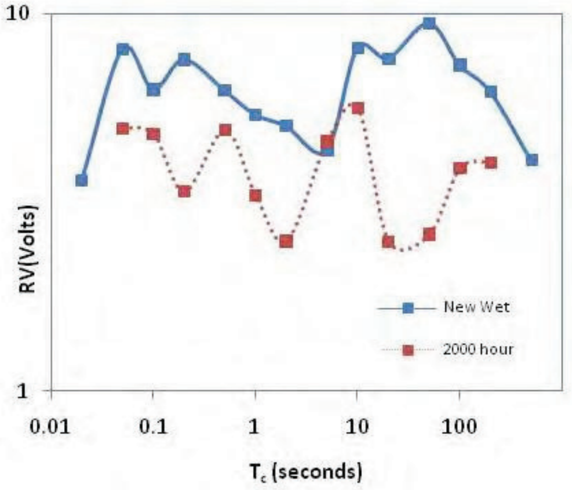
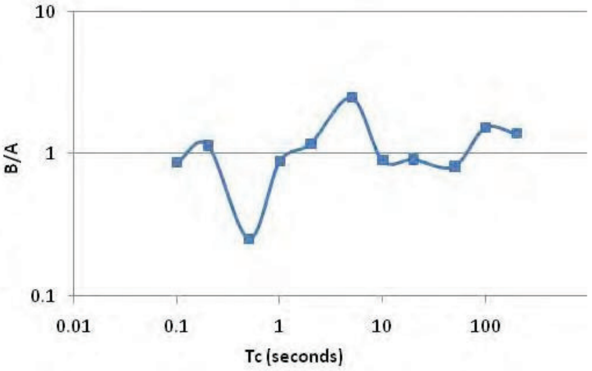


Fig. 3. Polatization spectrum of a new (wet) and a 2000 hours aged XLPE cable.

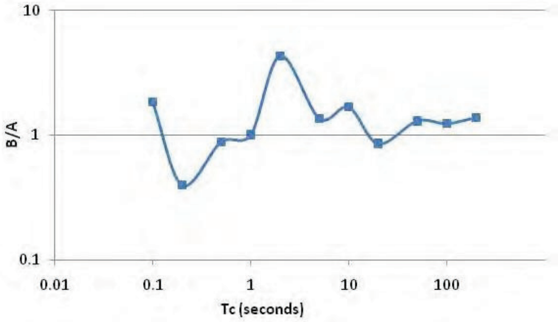
Fig. (4a) shows a division spectra of 3000 hour aged cable measured using charging voltage of 1.0 kV whereas Fig. (4b) shows this spectra measured at 2.0 kV. The first peak which should exhibit the effect of water treeing is confusing in both spectra. Either this hypothesis, which was based on simulation, needs further refinement, or the level of aging of cable is not yet adequate to fit on this model.

(b) Impact of Cable Aging on its Dissipation Factor

Dielectric spectroscopy in which degraded cables are tested by determining Tan δ (TD) values as a function of frequency (0.1 Hz to 10 Hz) as well as a function of voltage has been investigated in several research centers worldwide. In the present investigation this technique was also utilized to examine whether this method could detect water treeing degradation in the third generation cables as well, since some success has been reported in second generation cables which are badly deteriorated due to water treeing [11, 12].



(a)



(b)

Fig. 4. Division spectra of 3000 hours aged cable measured at 1.0 kV and 2.0 kV.

The first generation power polymeric cables were introduced in late 1960s and were equipped with an extruded conductor screen while the insulation screen was of graphite paint or conducting textile tape. These cables were steam cured and manufactured either through tandem or later through 2+1 extrusion processes. These cables possessed large number of voids and were thus susceptible to water tree degradation. These designs were abandoned in early 1980s when dry extrusion and curing was introduced along with use of cleaner materials. Cables produced so from 1980s up to late 1990s are called second generation cables. These are the cables that are now approaching the end of their service life and therefore are under investigation worldwide for their remaining life. The third generation cables were introduced by using extra clean insulation and semiconducting screen polymers free of trace amounts of impurities and/ or water tight designed XLPE cables. However, water trees occur in all types of polymeric cable designs though to a much lesser extent in the third generation cables. This is why for the third generation cables, the occurrence of low density of water trees makes the cable's condition assessment more difficult.

Past decade has seen lot of efforts being devoted on this technique and as a result several testing standards have been drafted [13,14]. However, these standards are confined to use of 0.1 Hz frequency VLF power supplies, since a correlation between an increasing 0.1 Hz TD and a decreasing insulation breakdown voltage level at power frequency has been reported [13]. According to reference [14], the TD values at U_o and $2U_o$ are measured and a differential dissipation factor ΔTD =

[TD(2U$_o$) – TD(U$_o$)] is calculated. The absolute TD and ΔTD values are used as figure of merit or compared to historical data to grade the condition of the cable insulation as **good**, **defective**, or **highly deteriorated**.

In the present investigation a third generation cable loop 220 m in length has been subjected to accelerated aging for 3000 hours. Fig. (5) shows variation of TD in new cable sample as a function of applied voltage at few selected frequencies. The impact of source frequency is also shown. A TD value of ≤ 0.4×10^{-3} at 0.1 Hz for new cable is slightly higher than the reported values for a new 15 kV rated XLPE cable reported in literature [13]. This could be attributed to the highly resistive stress cones connected on this cable. It is also clear that 0.01 Hz, VLF source exhibits almost an order of magnitude higher TD values as compared to TD values obtained at 0.1 Hz-VLF.

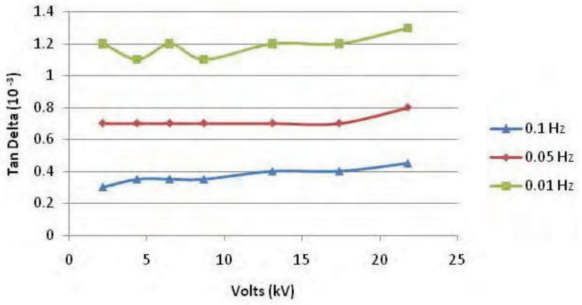


Fig. 5. Variation of TD in new XLPE cable.

Table (1) compares the TD values of aged cable in a frequency range of 0.1 to 0.01 Hz and measured at voltage steps of 0.25 U$_o$; 0.5 U$_o$; 0.75 U$_o$; 1 U$_o$; 1.5 U$_o$; 2 U$_o$ and 2.5 U$_o$ in a systematic manner. It is clear that aging from 2000 hours to 3000 hours has not produced any significant difference in TD values in this cable. In addition, a test procedure developed by Havidson et al [11, 12] was also tried. According to this procedure, if voltage is applied on water treed cable in steps up to 2.0 U$_o$ and then repeated at lower voltage level of 1.0 U$_o$, indicates a very distinct effect of increase in leakage current which results in higher values of TD at 1.0 U$_o$ that are equal to around the TD values obtained at 2.0 U$_o$. The occurrence of this phenomenon is indicative of severe water tree degradation of cable. We have tried this procedure on the 3000 hours aged cable but it did not exhibit any such effect and thus shows that this technique may not be successful on mildly deteriorated third generation cable.

References [13,14] claim that accessories that utilize stress grading materials with nonlinear voltage characteristics (i.e. high dielectric constant materials) may result in higher values of loss current at elevated voltages. Plots of tan delta versus voltage at 0.1 Hz for circuits containing such accessories will be indistinguishable from plots of highly degraded cables. On the other hand, accessories that geometrically grade the stress do not display such effect. In this context, it was shown earlier, that new XLPE cable with a length of 220m exhibited TD value of around 0.3×10^{-3} which is higher than 0.1×10^{-3} value reported for the new XLPE cable. This could be attributed to six units of high permittivity stress cones installed on this cable. To reduce effect of these stress cones, a 55 m long section of this cable with only two stress cones on it was subjected to TD measurements. Fig. (6) illustrates these results. It is clear that TD is reduced to 1.9×10^{-3}. However, an important aspect of these results is that though high permittivity accessories installed on XLPE cables exhibit marked effect on TD values measured at 0.1 Hz, but they do not exhibit such a pronounced effect at 0.01 Hz. This is certainly another advantage of diagnostic TD measurements at 0.01 Hz instead of 0.1 Hz. However, this interesting phenomena needs to be further explored.

Table 1. Comparison of TD data collected for 2000 and 3000 hours of cable aging.

	f = 0.1 Hz		f = 0.05 Hz		f = 0.01 Hz	
Aging Time Applied Voltage (kV)$_{rms}$	2000 hrs.	3000 hrs.	2000 hrs.	3000 hrs.	2000 hrs.	3000 hrs.
2.2	0.3 × 10^{-3}	0.24 × 10^{-3}	0.8 × 10^{-3}	0.8 × 10^{-3}	1.3 × 10^{-3}	1.3 × 10^{-3}
4.4	0.3	0.24	0.8	0.79	1.3	1.3
6.5	0.3	0.26	0.8	0.79	1.3	1.3
8.7	0.3	0.27	0.8	0.81	1.3	1.3
13.1	0.3	0.29	0.8	0.82	1.3	1.33
17.4	0.3	0.33	0.8	0.85	1.3	1.35
21.8	0.3	0.34	0.8	0.87	1.4	1.43

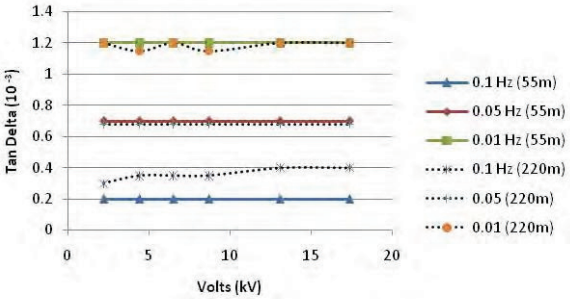


Fig. 6. Effect of stress cones on the TD values.

3.2 Measurement of Destructive Tests

The destructive tests comprised of an AC breakdown test as per HVTT protocol specified in AEIC-CS5-1994 [7] for new and 3000 hours aged samples as well as for water tree analysis. These cable samples were cut in 10 m lengths and prepared with proper stress cones and fitted one by one on a pair of deionized water high voltage cable terminations. Power frequency voltage was applied in 7.2 kV steps every five minutes till breakdown occurred. The breakdown voltage (V$_b$) as well as the average breakdown strength is compiled in Table (2). It is clear that E$_a$ of new cables is 33.79 kV/mm whereas it is 26.95 kV/mm for aged cables which shows a decrease in E$_r$ of only 20%.

The section of cable core for water tree examination from each aged cable sample was cut from near the breakdown point. No vented water trees were observed in 40 slices that were stained for microscopic examination. However, several bow-tie water trees (btt) were found in the middle of the aged insulation.

Fig. (7) displays one such slide showing bow-tie water trees. All such water trees with a length of ≥ 30 µm were measured and data compiled. Their lengths ranged from 30 µm up to 200 µm. The average density of bow-tie (btt) in this insulation was $0.02/\text{mm}^3$ which is much lower than usually found in highly deteriorated second generation XLPE cables. Our previous investigation [8] on second generation cables exhibited almost 50% reduction in E_r under the same aging parameters and duration. This shows that third generation cables comparatively have much less propensity toward water treeing and this is why the diagnostic techniques investigated here do not show promising results at this stage of aging.

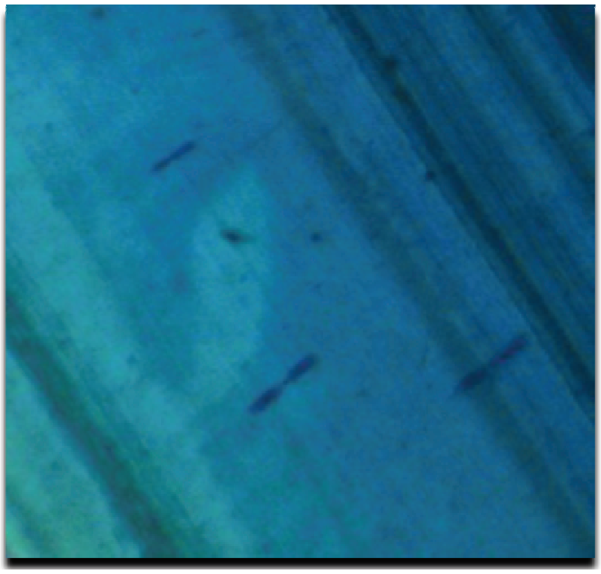


Fig. 7. Water trees detected in the aged cables.

Table 2. Comparison of breakdown para-meters of new and aged cables.

Sample #	V_b (kV_{rms})	E_b (kV_{rms}/ mm)	E_{ba} (kV/ mm)
N1	144.6	32.13	33.78
N2	145.1	32.24	
N3	166.4	36.98	
A1	123.3	27.4	26.93
A2	116.3	25.8	
A3	124.1	27.6	

N = New Sample A = Aged Sample

4. Conclusions

Multistress accelerated water tree degradation is being imparted on a 220 m long sample of 15 kV XLPE cable in the laboratory in a test rig specifically designed and implemented for this purpose. Diagnostic tests using three different techniques are being carried out at regular intervals. This cable has aged up to 3,000 hours and results indicate that water trees have grown up to lengths of 200 µm. All the three techniques comprising of RVM method, TD measurements obtained by VLF at 0.1 Hz and VLF dielectric spectroscopy, do not exhibit at this stage diagnostic response that could be related to water tree degradation. However, it is anticipated that more extensive degradation may lead to a diagnostic technique that will serve the best in the field.

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